THE APPLICABILITY OF DECISION CRITICAL PATH METHOD TO THE PUBLIC WORKS ENVIRONMENT

by

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ABSTRACT

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Submitted to the Department of Civil Engineering on December 7, 1970, in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

The purpose of this study was to investigate the applicability of Decision Critical Path Method for planning, scheduling and controlling construction and renovation projects that are accomplished in the Public Works environment.

Both Critical Path extensions and Decision Critical Path Method are discussed within the framework of planning, scheduling and control functions. The mathematical basis and solution techniques for Decision Critical Path Method are presented.

The interaction of the model and its characteristics with the organizational structure are considered along with the resulting cost impacts.

The model was applied to a building renovation project in which the network consisted of twenty-four decision nodes, and one-hundred and thirty activities. The resulting initial solutions to the network provided a reduction in time of 30% and a reduction in cost of 36%.

It was concluded that the Decision Critical Path Method should be used for planning and scheduling projects but that model limitations and education of involved personnel must be considered. Further computer based model development and project applications are suggested.

Thesis Supervisor. . . . . .Albert G. H. Dietz

Title. . . . . Professor

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CHAPTER 1
INTRODUCTION

Decision Critical Path Method (DCPM) has been proposed by Crowston and Thompson[1] as a method for simultaneous planning and scheduling of projects. However, to date the method has not been used in practice. It is, therefore, the objective of this thesis to show that DCPM can be used on construction projects within a Public Works environment and to show its strengths and weaknesses in an actual application. In addition, the experience gained through the application will provide greater insight and direction to possible areas of future development and application.

In considering the general Public Works environment, a set of general criteria must be set forth that both define and apply to the Public Works organizational and operating environment. First, the Public Works organization is responsible for maintaining and revitalizing a specified set of physical facilities. These physical facilities consist of, but are not limited

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[1] W. Crowston and G. L. Thompson, "Decision CPM: A Method for Simultaneous Planning, Scheduling and Control of Projects," Operations Research, Vol. 15, No. 3, May-June 1967.

to, buildings, grounds, utilities systems and roads. Second, the organization has within its capability most of the general building and construction trades personnel with which to accomplish the physical facilities maintenance and revitalization. Third, it has a contractual capability to accomplish specific tasks by utilizing "out-of-house" organizational capabilities.

Based on the above criteria, it is readily apparent that there are a large number of organizational entities in existence which meet the criteria and as the word "public" implies, operate with public funds in a governmental framework. These Public Works organizations exist at the city, state and federal levels of government, and public institutions. In addition, there are similar organizations in existence that meet the above criteria but are in the private sector of the economy, i.e. physical plant departments in large corporations and universities.

With this potentially broad base for the general application of DCPM, selection of a Public Works organization and a somewhat typical project was considered to be essential if meaningful results and conclusions were to be made about DCPM's applicability.

With regard to the selection of a Public Works organization for testing the applicability, it was considered necessary to select an organization which, in addition to meeting the basic criteria, had a sufficient size and operating environment to offer a general range of potential applications. In considering the application of DCPM to a specific project within the Public Works organization, selection of the project had to take into account (a) whether the project was generally typical to the Public Works environment, (b) its size, and (c) its complexity. Thus, by taking into explicit consideration these factors, the application of DCPM to the selected project in the selected organization should produce results and conclusions which should form a foundation for assessing the potential future applicability in the Public Works environment.

As a representative of the Public Works environment, the author selected the U. S. Navy Public Works Center (PWC) at Newport, Rhode Island, because of his familiarity with the organization and its operating environment. In addition to meeting the prescribed prerequisites outlined earlier in this chapter, the PWC has several unique operating characteristics. The PWC meets the first of the prerequisites listed in that it is responsible for

maintaining and revitalizing the entire Newport Naval Base which consists of 150 buildings (1.5 million square feet), 50 miles of roads, 530 housing units (1.8 million square feet), base-wide utility systems, and waterfront structures. This represents, in municipal terms, a city of approximately 25,000 people. In accomplishing its basic responsibility, the PWC meets the second pre-requisite by maintaining a 300-man work force that has basically all the normal building and construction trades represented. The contractual requirement is met in that the PWC can contract with local designers, contractors, and suppliers for those tasks which the organization cannot perform because of resource constraints, e.g. lack of a specific skill within the organization or lack of men, or equipment, during a specific time frame.

One of the interesting features of the PWC is that although it is a non-profit organization, it does operate on a zero-profit motive basis. This feature exists because the PWC is a separate command structure that provides services to all the operating commands on the Base. These operating commands or customers budget for maintaining and upgrading their individual facilities and then buy services from the PWC. The PWC performs the work and bills the customer at a price consisting of

labor, materials, and operating overhead cost. Since the PWC has contractual authority and maintains a service function, the customers pressure the organization to maintain an efficient operating posture which is competitive with local contractors.

Discussion of the selection, description, and application of DCPM to a representative project will be presented in Chapter 5.

CHAPTER 2
PLANNING AND SCHEDULING

Since the Public Works organization is responsible for maintaining and revitalizing a set of physical facilities, it becomes quite evident that this responsibility extends over the total range of the facility's life cycle. This life cycle is graphically portrayed in Figure 1. The current use of existing planning and scheduling models such as CPM and PERT[2] have received extensive use in the region of construction and to lesser degrees in the design process and maintenance/renovation area. The main interest of this thesis is to show the relative applicability of DCPM within the life cycle with a representative project selected from the renovation region.

With the life cycle framework, the general operational use of planning and scheduling models can be visualized as in Figure 2. The range over which these

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[2] Critical Path Method (CPM) was developed by du Pont and Remington Rand in 1956 while Program Evaluation and Review Technique (PERT) was developed by the U. S. Navy for use on the Polaris project at about the same time.

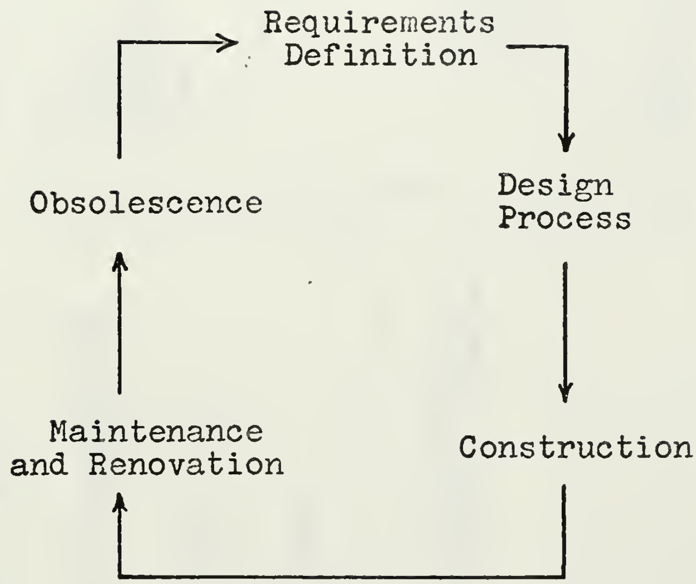

FIGURE 1

FACILITY LIFE CYCLE

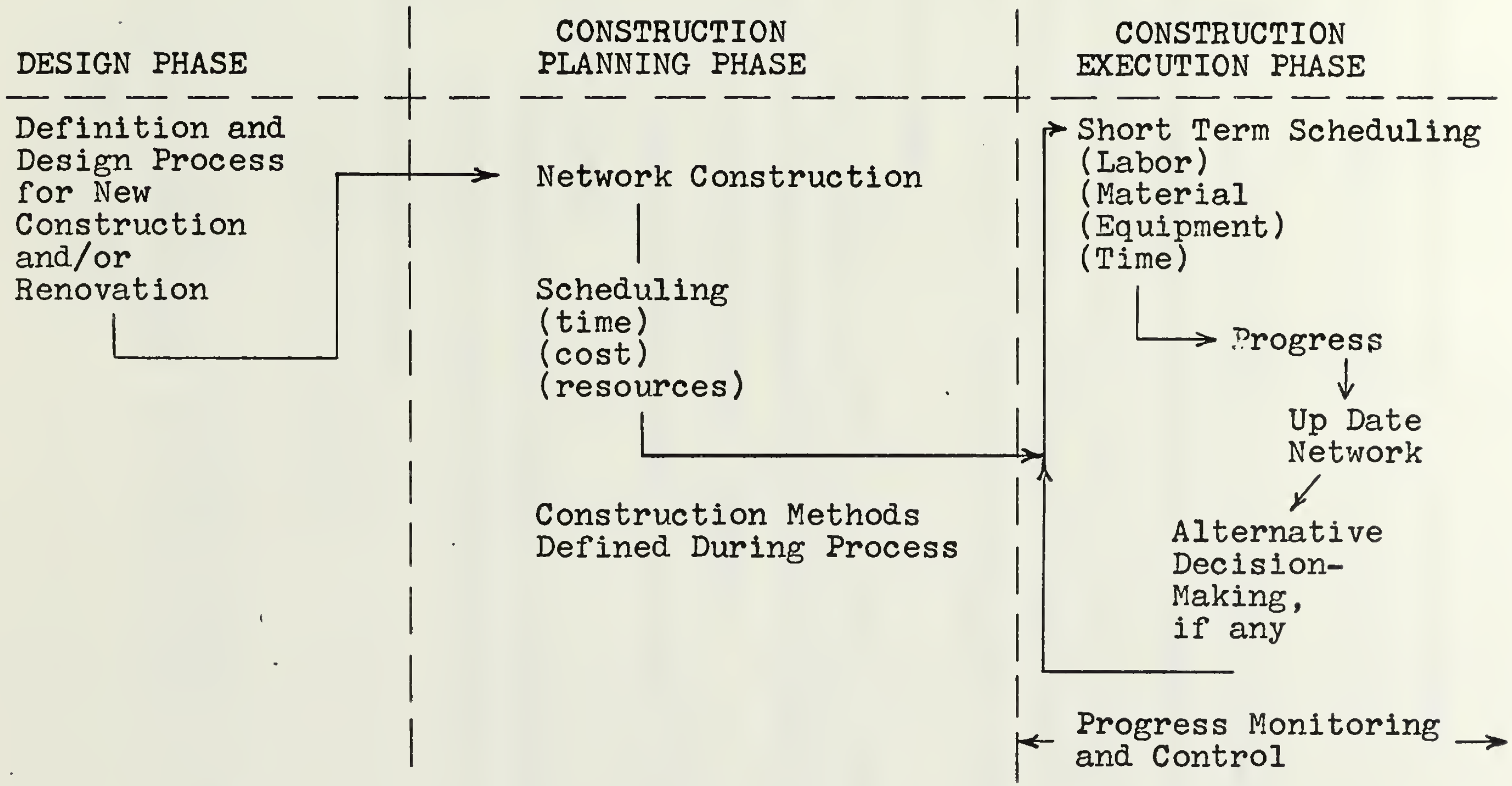

FIGURE 2

PLANNING/SCHEDULING MODEL UTILIZATION

models operate can be the three phases shown in Figure 2, but of particular interest is the use during the construction planning phase and the construction execution phase.

First, considering the construction planning phase, Shaffer[3] states that two distinct functions occur; namely, planning (network construction) and scheduling. Planning is defined as determining <u>What</u> should be done, whereas scheduling is determining <u>When</u> the operations should be done.

If one is using a model such as CPM, Shaffer[4] considers the process during this phase to consist to a series of application levels, namely:

(1) Describe the project in terms of dependencies among operations,

(2) Determine the schedule of operations,

(3) Determine those operations which control significant target dates,

(4) Analyze the schedule,

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[3] L. R. Shaffer, J. B. Ritter, and W. L. Meyer, <u>The Critical Path Method</u> (New York, 1965), p. 6.

[4] <u>Ibid</u>., p. 140.

(5) Replan the project if the analysis so indicates,

(6) Allocate resources to the project in an efficient manner for the schedule development, or determine schedule changes required by resource limitations.

(7) Analyze different schemes for part or the whole project.

Further analysis of these seven levels of application results in the realization that a continuous decision-making process is in effect during the construction planning phase which involves either explicit or implicit recognition of construction methods to be used for each activity in the network. Since this decision-making process is considering the variables of time, cost and resources associated with each activity, the basic CPM model has been extended to consider explicitly (a) time-cost tradeoffs and (b) resource leveling.

With the basic objective of reducing the project completion time the time-cost tradeoff model allows the planner to consider alternative methods of accomplishing critical and near critical activities, each alternative having a discrete duration and cost. Then, by

considering all of these alternatives within the project network, it is possible to map out a cost versus duration function. This function is then used to determine the method of accomplishing the project. If the following assumptions are met,

(1) the "true time cost relationship of a typical project activity" is a continuous, convex function,

(2) the activity cost functions are independent,

(3) each activity cost function can be approximated by a piece wise linear function,

then the project cost function can be formulated using Kelley[5] and Fulkerson[6] linear programming formulation. However, if the assumption of continuous convex time-cost functions is inappropriate, then the more general activity time-cost functions can be handled using Meyer and Shaffer's[7] zero-one integer variable linear

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[5] J. E. Kelley, Jr., "Critical Path Planning and Scheduling: Mathematical Basis," Operations Research, Vol. 9, No. 3 (1961), 296-320.

[6] D. R. Fulkerson, "A Network Flow Computation for Project Cost Curves," Management Science, Vol. 7, No. 2 (January 1961), 167-179.

[7] W. L. Meyer and L. R. Shaffer, "Extensions of the Critical Path Method Through the Application of Integer Programming", Report issued by the Department of Civil Engineering, University of Illinois, Urbana, Illinois, July 1963.

programming formulation. In this formulation, integer variables are used directly for discrete points, with a variable assigned to each discrete alternative and given the value of one if the activity is to be crashed. The project cost curve can then be calculated using a general integer programming routine. This later "time-cost tradeoff" model is very similar to the DCPM in that both are concerned with discrete point time-cost trade-offs and utilize integer variables associated with each alternative. However, the critical difference between the two models lies in the fact that DCPM does not require each of the various alternatives for each decision activity to have the same predecessor-successor relationships. Consequently, the time-cost function and the predecessor-successor relationship for each alternative must be specified.

The second area of extensions to the basic CPM model addresses the issue of resource allocation during the scheduling phase. There are two basic problems involved; one deals with "leveling" resource demands with a constraint on the total project duration while the second problem deals with the minimization of the project duration with a constraint on the total availability of key

resources. The approach taken by most of these resource constrainted models is based on heuristics or "rule-of-thumb" for allocating the available resources to the project activities. Moder and Phillips[8] describe several procedures which form the basic heuristics for solving the above two problems. A further extension to the resource constrainted approach is to consider more than one project simultaneously. Two existing models for handling the multi-project problem are RAMPS[9] (Resource Allocation and Multi-project Scheduling) and SPAR[10] (Scheduling Program for Allocation of Resources).

Although both of the model extensions to CPM are used during the construction planning phase, the emphasis of variables to be explicitly considered are different. The time-cost tradeoff models, as the name implies, are concerned only with activity times and costs. Resource

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8 J. J. Moder and C. R. Phillips, Project Management with CPM and PERT, 3rd ed. (New York, 1966), p. 107.

9 J. Moshman, J. Johnson, and M. Larsen, RAMPS, A Technique for Resource Allocation and Multi-project Scheduling, Paper presented at proceedings of 1963 Spring Joint Computer Conference.

10 J. D. Weist, "A Heuristic Model for Scheduling Large Projects with Limited Resources," Management Science, Vol. 13, No. 6 (February 1967), B-359-B-377.

applications are only considered for developing alternatives for activities but no formal mechanism exists for constrainting the available resources among several competing activities. Likewise, the resource allocation models are only concerned with sequential allocation of available resources over time.

DCPM, as will be shown in detail in Chapter 3, is concerned only with time and cost which makes it more similar in nature to the "time-cost tradeoff" models than the resource allocation models, except it is not as restrictive in predecessor-successor relationships. The model cannot accomplish resource leveling as such throughout the total project but indirectly can be used to consider different levels of resources for specific decision activities.

Since the PWC has many projects in progress at any particular time and has a fixed pool of labor and equipment over the short-term, project scheduling is of necessity a multi-project, resource constrainted environment. In fact, Greenwald[11] has shown the general applicability of using the RAMPS model in scheduling

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[11] James M. Greenwald, Toward a Mechanized Facilities Maintenance Control System for the United States Navy (Unpublished Massachusetts Institute of Technology Master's Thesis, June 1968).

projects at the PWC. Thus, since DCPM is restricted to single projects with non-resource constraints, explicit recognition of these limitations must be considered when using the model in the PWC environment and will be discussed in Chapter 4.

CHAPTER 3
DECISION CRITICAL PATH METHOD

In conventional CPM analysis, the planner makes decisions either explicitly or implicitly as to the specific method for performing each activity within the project. These decisions are made either during the planning phase (network construction) or during the scheduling phase (activity duration and cost determination). This process culminates in a project planned and scheduled that is to be accomplished in accordance with the results of the informal decision-making process that transpired. Only if the resulting completion date is out of line, is there another iteration in the decision-making process; but this time only on selected activities in what is more formally known as a "time cost trade-off" analysis.

Crowston and Thompson have developed a model called DCPM which incorporates a decision mechanism into the traditional CPM technique. As stated in their paper:

> If there are a number of competing methods of performing some of the jobs, each method having a different cost, a different time, duration and different technological dependence, we shall include these in the project graph, rather than making the decisions in advance. Then in the scheduling phase, we shall consider

> the effects of all alternative methods of performing a task on the total cost of completing the project and choose those alternatives which minimize this cost.[12]

Thus, the decision making process for selecting an alternative is made explicitly in light of its effect on the overall project cost and completion date, rather than on some implicit reason or the lowest cost alternative.

3.1 Mathematical Basis of DCPM

The mathematical basis is taken from the paper by Crowston and Thompson[13] and is included to outline the essential elements of the method. For more detail, refer to the original paper.

> Let $J = (S_1, S_2, S_3 \ldots)$ be a set of job sets (activity sets in CPM terminology) that must be accomplished to complete a project. Some of the job sets are unit sets, $S_i = (S_{i1})$; that is, no alternatives are available; while other job sets have available alternatives,
>
> $$S_i = (S_{i1}, S_{i2}, S_{i3} \ldots, S_{ik(i)}) \qquad (1)$$

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[12] Crowston and Thompson, p. 407.

[13] *Ibid.*, pp. 408-410.

Since a selection must be made from the job set, there is a corresponding decision variable, d_{ij}, for each variable in the job set.

$$d_{i1},\ d_{i2} \cdot \cdot \cdot \cdot\ d_{ik(1)} \cdot \tag{2}$$

The decision variable has the property that:

$$d_{ij} = \begin{cases} 1 \text{ if alternative } S_i \text{ is to be performed} \\ 0 \text{ if otherwise} \end{cases} \tag{3}$$

If the jobs within the job set, S_i, are mutually exclusive, that is, if one job is to be performed, then the remaining jobs in the set will not be performed, this condition is expressed by:

$$\sum_{j=1}^{k(i)} d_{ij} = 1 \tag{4}$$

If all of the job sets are unit sets (no feasible alternatives available), then the project graph reduces to an ordinary CPM project graph.

If, however, there are one or more decision job sets (more than one feasible alternative available), then a selection of desired alternatives to be performed must be made. When the selection of the desired alternatives has been made for all such decision sets, the resulting project graph reduces to the CPM graph. It should be recognized that feasible alternatives need not be restricted to that condition of mutually exclusive interdependence as expressed in Equation (4) above. In fact, consideration of alternatives that are of different technology or method will complicate the predecessor-successor relationships and thus create more expanded relationships than that expressed in Equation (4).

Associated with each job, S_{ij}, are a duration time, t_{ij}, and a cost, C_{ij}. The project has a given completion date, D. The project may also have an associated reward payment and a penalty cost; however, this condition is not required. The reward payment, r, would be in terms of dollars per day for each day the project is completed before the completion date, D.

Conversely, the penalty cost, p, would be the assessed loss in dollars per day for each day the project continues beyond the completion date. If W_F represents the early start of job FINISH, then the DCPM network can be formulated as an integer programming problem for determining lowest cost project graph and its critical path.

The objective function:

$$\text{MIN } Z = \sum_{i=1}^{h} \sum_{j=1}^{k(i)} d_{ij} \ C_{ij} - r \ W_F^- + p \ W_F^+ \qquad (5)$$

Subject to Equations (3) and (4) above and

$$W_F - W_F^+ + W_F^- - D = 0 \qquad (6)$$

Because of normal precedence relationships, additional constraints in the form

$$W_i + t_i = W_j \qquad (7)$$

Where W_i is the early start of job S_i, t_i is the duration of W_i, and W_j is the immediate successor. Multi-job sets constraints are in the form

$$-M \ (1 - d_{ij}) + W_{ij} + t_{ij} \leq W_m \qquad (8)$$

Where M is a large number such that the inequality is restrictive only if $d_{ij} = 1$. Thus, if S_{ij} is not selected, the inequality does not constrain the variables, and the S_{ij} path with its successors will not be considered.

This integer programming formulation of the DCPM network allows for the direct solution taking into consideration the selected decision alternatives, all imposed constraints and the reward payment or penalty costs. The resulting solution represents the minimum cost network and the associated decision alternatives for accomplishing the project.

3.2 DCPM Network Reduction and Solution

The formulation of the DCPM network, which consists of Equations (1) through (8), is that of an integer programming formulation. The solution can be accomplished by either integer programming techniques or by Branch and Bounding techniques. Integer programming techniques were used by Smylie[14] to solve a

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[14] R. E. Smylie, The Application of Decision CPM to Incentive Contracts (Unpublished Massachusetts Institute of Technology Master's Thesis, June 1967).

DCPM network consisting of 55 activity nodes and 5 decision nodes and proved to be exceedingly slow in computation time. Therefore, the search for more efficient computation algorithms has proceeded in the area of Branch and Bounding techniques. Branch and Bounding, also known as Combinatorial Programming or Controlled Enumeration, is essentially an intelligently structured search of the space containing all possible solutions. The two underlying principle concepts to this technique are: (1) the use of a controlled enumeration technique for implicitly considering all potential solutions, and (2) the elimination from explicit consideration any potential solution which is known to be unacceptable due to bounding or feasibility considerations.

Before applying the Branch and Bounding technique, the first step is to reduce the DCPM network. Crowston[15] has shown that all non-decision jobs may be eliminated from the original project network, thereby producing an equivalent reduced network. This is accomplished by first considering the longest directed path connecting any two decision activities but not passing through any other decision activity. This path is termed the "zero-

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[15] W. B. Crowston, "Decision CPM: Network Reduction and Solution," Alfred B. Sloan School of Management Working Paper (April 1970), No. 457-70.

order subpath". Next, all zero-order subpaths are determined for the network, then the reduced network is developed by considering only all decision activities and all zero-order subpaths. The reduced network is then the equivalent of the original network in that the resulting early start times for the decision activities are the same in both networks.

From the reduced network, the Branch and Bounding Technique is used to determine the lowest value, Z., for the network. This is accomplished by first transforming the reduced network into a tree search diagram. That is, considering the first decision node, the branches emanating from it represent each activity alternative. Then, each succeeding decision node with its activity alternatives is added to each of the preceeding alternatives. This procedure is continued until all decision nodes in the reduced network are transformed to the tree search diagram. Figure 3 illustrates a tree search diagram.

The generation of the total tree search diagram would allow for an explicit evaluation of all possible solutions. However, the efficiency of the Branch and Bounding Technique lies in the basic underlying

principle that the total tree search diagram need not be generated but instead only those additional branches need to be added to the paths which are not bounded or infeasible. Thus, only the most promising paths are explicitly evaluated.

Crowston and Wagner[16] have developed within the Branch and Bounding Technique an algorithm which generates and evaluates the tree search diagram for the solution. This algorithm is called the Partitioning Algorithm and a capsuled outline of that presented in their paper[17] follows:

> Partial Solution (Partial Path Completion): P_n^k is a set of n decisions, $d_{\alpha(m)j} = 1$ where $m = 1,\ldots n$, k is a bookkeeping label, and α is a vector of decision node labels in some order.

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[16] W. B. Crowston and M. H. Wagner, "Boeing Research Report, A Comparison of Tree Search Schemes for Decision Networks," Alfred B. Sloan School of Management Working Paper (March 1969), No. 380-69.

[17] Ibid., pp. 4-18.

An augmentation to the partial solution, P_n^k is the choice of an activity alternative for the succeeding decision node, $\alpha(n+1)$, to be done in conjunction with P_n^k.

$$P_{n+1}^{k'} = P_n^k \, d_{\alpha(n+1)j}$$

A Completion (Completed Path): $P_N^{K'}$ of P_n^k results from a series of augmentations such that a decision is made for each node.

Then, for each completion, $P_N^{K'}$, there is a corresponding completion time W_F^K and a cost C^K. The objective function, equation (5), then takes on a value, Z^K. In evaluating each P_n^k, if a previous value, Z^*, is such that $Z^* < Z^k$, then P_n^k is bounded and need no longer by considered.

The decision nodes are partitioned into two sets: B, the Branch and Bound Set, and Q, the cheapest alternative set.

The algorithm proceeds as follows:

Step 1: $Z^{*} = \infty$.

$\gamma = (1)$

$P_0^1 = (0)$, $Z^1 = 0$

Step 2: $K = \gamma(1)$; current solution is P_n^k

If $Z^k > Z^*$, go to Step 6

If $Z^k \leq Z^*$, go to Step 3 if $n < b$

go to Step 2A if $n = b$

go to Step 5 if $n = N$

Step 2A: Determine Q_b^k; $P_N^{K'} = P_p^k \quad Q_p^k$, and $Z^{k'}$

Step 2B: If $W_F^{k'}$ of $P_n^{k'} = W_F^k$ of P_b^k, go to Step 5 with P_N, otherwise go to Step 2C.

Step 2C: Determine critical path for $P_N^{K'}$. Place those nodes of Q which are critical into B. Go to Step 2.

Step 3: $i = \alpha(n+1)$

Step 4: Evaluate each of the augmentations $P_n^k \cup d_{ij}$ by testing each for:

a. feasible?

b. $Z^{k'} \leq Z^*$?

Save the solutions which pass the two tests, and insert the new labels K' at the top of the list, γ. If no unbounded feasible solutions, go to Step 6, otherwise go to Step 2.

Step 5: $Z^* = Z$; revise γ by putting $\gamma(1)$ at the end and moving all other elements up one position. Go to Step 7.

Step 6: Delete $\gamma(1)$ from γ and move all other elements up one position.

Step 7: Finished? If not, go to Step 2.

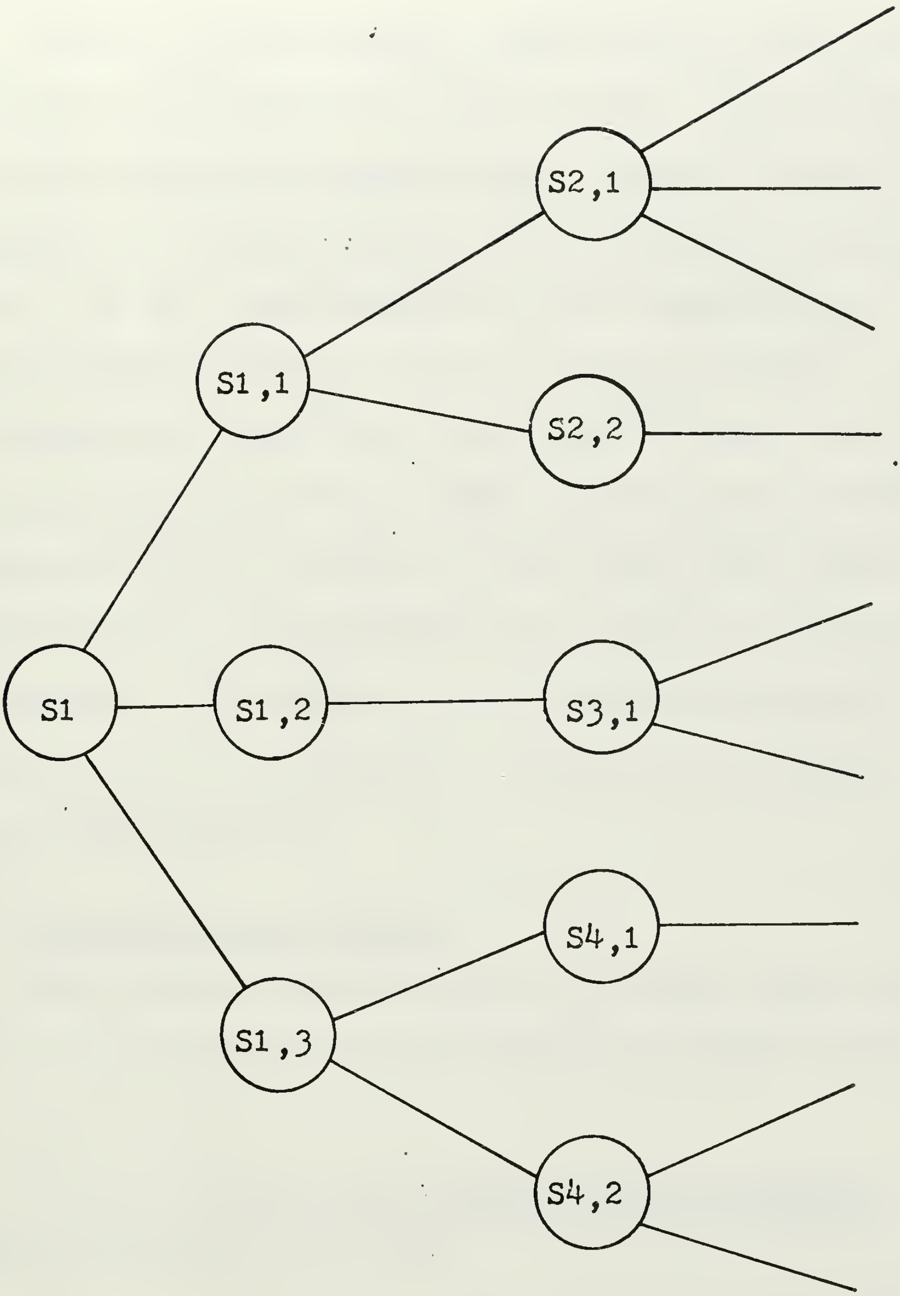

FIGURE 3

TREE SEARCH DIAGRAM

CHAPTER 4
CONSIDERATIONS

Prior to implementing a model such as Decision Critical Path Method in a Public Works organization, or for that matter, any organization, several issues must be addressed. These issues may be functionally categorized into: (a) the implications for the organization, (b) the model characteristics, and (c) the cost impacts. Studies conducted by Hilton[18] and Martinelli[19] showed that the successful use of CPM and PERT within private industrial organizations was related to the effort that was exerted in identifying and addressing the issues in the above categories. Since DCPM is an enriched extension of basic CPM, it is necessary to explore the various issues which impact the PWC.

4.1 Organizational Issues

The primary issues facing the Public Works management in considering the application of DCPM is who in

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[18] M. W. Hilton, The Use of PERT in Industry (Unpublished Massachusetts Institute of Technology Master's Thesis, June 1966).

[19] S. A. Martinelli, Construction Industry User Feedback Analysis of the Critical Path Method Unpublished Massachusetts Institute of Technology Master's Thesis, February 1965).

the organization will use the model and what are the interfaces, benefits, and impacts? Before addressing this issue, it is necessary to consider Anthony's[20] general concepts of management and operational control. Anthony defines management control as "the process by which managers assure that resources are obtained and used effectively and efficiently in the accomplishment of the organization's objectives".[21] Operational control, on the other hand, is "the process of assuring that specific tasks are carried out effectively and efficiently".[22] With these general definitions, it is quite obvious that the shop forces of the PWC are naturally within the confines of operational control. That includes the individual trade supervisors. When only considering a specific project, both the project manager and superintendent are within operational control. However, since the PWC workload consists of many projects in progress simultaneously, these two specific personnel also operate within management control.

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[20] R. N. Anthony, Planning and Control Systems: A Framework for Analysis (Boston, Massachusetts) 1965.

[21] Ibid., p. 17.

[22] Ibid., p. 18.

With this basic framework, the issue of who will use DCPM can now be addressed. Since DCPM has two fundamental characteristics - namely, a decision making mechanism and a scheduling mechanism, it becomes clear that the model will extend into both regions of management control and operational control. Depending upon the class of decisions incorporated for a specific project, the decision making responsibility may be either in management control or in operational control. Thus, the project manager, project superintendent and building trade supervisors will be directly involved with the use of the model, both the decision making mechanism and the scheduling mechanism. The organizational hierarchy above the project manager level will have decreasing involvement.

The identification of interfaces to be addressed can most appropriately be categorized into computers, people and accounting. First, solution of a DCPM network with any degrees of complexity becomes a combinatorial programming problem, thus requiring a computer. Although the PWC does not own a computer, it rents time from a local command that has a Honeywell H-200 computer. Although the H-200 is capable of handling the DCPM programs, the selected project network was run on MIT's Compatible-Time Sharing System (CTSS) using an IBM 7090.

The interface of the model with people can be reduced to one of education. As with normal CPM/PERT, Hilton[23] and Martinelli[24] stated that successful implementation and operation of those techniques were characterized by an extensive educational effort. This aspect is doubly important because in CPM/PERT application, the issue was one of improving individual's scheduling technique and met with immediate resistance in the form of "what's wrong with the way I'm scheduling now?". With DCPM, the implication is one of insufficient decision-making capability of the affected personnel. Thus, educational effort must be of primary importance.

The interface of the model with the existing accounting system can be broken into two aspects, cost estimating and cost gathering. Since the most important fundamental characteristic of the model, that of decision-making, relies on accurate estimates of time and cost, it is necessary to examine the method and reliability of these estimating procedures presently in use. Although the time/cost estimations accomplished by the PWC estimators are accomplished after the design phase of a project has been completed, the estimates are

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[23] M. W. Hilton, op. cit.

[24] S. A. Martinelli, op. cit.

based on building trade category and unit quantity of labor, material, and equipment required for the total project instead of for each individual activity on the CPM network. This procedure is used because the majority of the projects are of such a small nature that scheduling is done in the job shop manner vice the project method. For those projects that are to be planned and scheduled using CPM techniques, the time/cost estimates are modified to suit the network developed. Although most of the estimates are directly translatable because the activities are confined to single trade skills, modification must be made to those activities that require multi-trade skills. This same procedure, although not the most efficient nor desirable, can be used for generating the time/cost estimates for the DCPM network.

Since the time/cost estimating method used is based on Engineered Performance Standards,[25] the reliability of these estimates will be discussed in the model characteristics sections.

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[25] Anonymous, Engineered Performance Standards, Engineers Manual, NAVDOCKS P-700, September, 1963, Department of the Navy, Bureau of Yards and Docks, Washington, D. C.

The second fundamental characteristic of the model, scheduling, is the basic CPM technique. Early and late start dates of every activity are employed to schedule labor, materials and equipment for the successful accomplishment of the project. These times are, of course, generated for specific scheduling of each activity once decisions have been made as to which alternatives will be selected. Using these times, direct operational control can be exercised over the duration of project progress. However, although time is directly controlled, the model suffers the same disability in the cost control area as ordinary CPM. This disability is the result of the interface between activity cost accounting and organizational accounting. In the case of the PWC, the costs are gathered by functional organizational elements and summarized by project. Thus, the detailed information of costs by each activity within a project is lacking, thereby rendering cost control by individual activity useless. For an excellent discussion on network based cost control systems, the author suggests Moder and Phillips'[26] discussions.

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[26] J. J. Moder and C. R. Phillips, Project Management with CPM and PERT, 3rd ed. (New York, 1966), Chapter 8.

In assessing the anticipated benefits and impacts, one must consider the current methods of planning and scheduling, the degree of elimination of the interfaces, and the resulting changes in operating procedures. As stated previously, the majority of the PWC workload is of a minor project effort in both maintenance and new construction (alterations), and so planning and scheduling are accomplished in the traditionaly job shop manner. However, on those larger nature projects, CPM techniques are used. Thus, transition to use of DCPM would be relatively easy assuming an adequate educational effort was launched to expand the awareness for explicitly considering all reasonable alternatives. But, it must be recognized that along with considering more alternatives comes an increased effort on the part of the planners and estimators to develop the corresponding time and cost estimates. However, this resulting expanded effort will produce the most significant benefit from using DCPM - this is the increased communication and explicit awareness of the exact methods to be used in accomplishing the project.

4.2 Model Considerations

The issues which need to be considered in model selection and implementation must of necessity deal with the limitations of the model due to its fundamental assumptions. To determine the DCPM model applicability requires an examination of the limitations on activity time, cost, resource balancing, and execution phase use.

4.2.1 Activity Times

The assumption used in the model for stating activity times is that the time is deterministic rather than probabilistic. This deterministic characteristic is what generally distinguishes CPM models from PERT models. Thus, in order to use the model, one must place a high degree of reliability in the time estimates. In the case of the PWC, times are generated using Engineered Performance Standards[27] which are developed from "observing craftsmen at work and measuring that work through the application of approved industrial engineering techniques". Although the standards are "set as a range of time rather than a precise time in which to accomplish

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[27] Anonymous, Engineered Performance Standards, op. cit., p. I-3.

a specific amount of work", the range is generally taken to vary not more than 10% about the mean of the range. Thus, although the times are recognized to be probabilistic in nature, the limiting range is accurate enough to consider the time as determinate. This is particularly true when considering that the detailed breakdown of activity times is such that generally the time developed is not more than 5 or 6 days.

4.2.2 Costs

a. The second input into the DCPM model is costs; activity costs and, when applicable, reward payments and penalty costs. The determination of labor, materials, equipment and indirect costs associated with each activity are generally directly generated from the time estimates. Some modifications are required if the estimates are on a unit quantity basis rather than by activities. The question of how to allocate overhead costs to each activity is more complex. Because overhead costs are not in general directly related to every specific project activity, the allocation may be:

(1) made on a pro-rata basis to every project activity,

(2) excluded from the individual activities and applied to the total project, or

(3) applied to those readily identified activities and the remainder to the total project.

Since the PWC includes a fixed overhead charge in the wage rate, the allocation of the overhead costs was included in every activity. Although this pro-rata allocation may not be the precise method, it does allow for direct comparison of total project cost of the various alternatives of accomplishment.

b. It should be added that if cost estimating is accomplished on a unit quantity basis as is done by the PWC, then activity costs must be developed by modifying the unit quantities to activity quantities and in conjunction with the time estimates explicitly consider labor and equipment requirements for each activity.

c. Use of the model in the construction execution phase for cost control is quite impractical for the PWC case because the cost collection is accomplished only on the project level by labor class; thus, cost control by detailed activity cannot be accomplished. If, however, an organization has a

network based cost accounting system that collects costs on an activity basis or activity group basis, then the model can be used for cost control.

4.2.3 Resource Balancing

As previously shown, the model does not have a formal mechanism for performing resource allocation. Thus, an appropriate method for considering resource constraints is to: (1) develop activity time and costs based on a specified construction method using "normal" labor and equipment levels, (2) use DCPM to select the appropriate alternatives, (3) generate a working schedule with resources shown, (4) analyze the resulting schedule for resource constraints, (5) adjust activity time and costs with new level of resources and/or methods as appropriate, and (6) go back to Step 2 and iterate. It should be immediately obvious that this method is only appropriate when the number of constrainting resources and activities involved is small; otherwise, use of a resource allocation model is dictated.

4.2.4 Execution Phase Use

a. As can be seen in Figure 2, for the model to be more than just a planning tool, it must be operable in the execution phase. In particular, it must be capable

of producing short-term schedules in terms of labor and equipment to aid the management and control of the project. Additionally, although not of vital necessity, the model should be easily updatable in order to reflect existing progress and procedure with the sequential decision-making process. For example, if the project progress proceeded exactly as originally planned, the initially selected decision alternatives would be performed and there would be no need for re-evaluating the network. However, this happy situation is rarely the case, thus requiring a periodic updating and re-evaluation of the network and decision alternatives in light of the present progress.

b. Development of the model to date has centered around the search for more efficient algorithms for solving the combinatorial programming problem which is set up when the decision alternatives are incorporated in the network. Thus, the operating computer programs available provide the selection of the appropriate decision alternatives but no scheduling outputs for use in the execution phase, leaving the model inoperable as a tool for short-term scheduling. To use the model on a particular project with the existing programs would

restrict one to the construction planning phase since the output is in terms of only the selected decision alternatives; that is, the DCPM network is reduced to a normal CPM network. To obtain the desired scheduling information would then require using an existing CPM program such as the Integrated Civil Engineering System (ICES) Project I[28] and the CPM network obtained from the DCPM run as input.

4.3 Cost Impacts

The third issue that must be considered before implementing the model is "what are the total costs involved?". Since every Public Works organization faces a different situation, it would be impossible to determine the specific cost impacts; however, some general comments can be made about the cost impacts associated with PWC Newport. The PWC presently has an estimating staff so the only additional costs would be in:

a. educational effort

b. effort required to identify alternatives and

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[28] Robert L. Daniels, "ICES Project I, Engineering User's Manual," MIT Department of Civil Engineering Report R68-11 (August 1968).

develop the corresponding time/cost estimates, and

c. computer costs.

As will be shown in Chapter 5, the estimation and computer effort is quite small; however, as stated previously in this chapter, an extensive educational effort would be required.

CHAPTER 5
PROJECT APPLICATION

5.1 Project Description

The project selected for applying DCPM was the renovation of an existing 270 ft. by 100 ft. two-story wood ARCH building. The main floor was essentially equally divided into two parts, (a) the customer's service department, and (b) an obsolete mechanical equipment area. The second floor consisted of a general storage area and the building's heating, ventilating and air conditioning equipment. The project came into existence due to the customer's desire to expand his operation into the mechanical equipment area and architecturally renovate his existing area. Thus, the project entailed removal of the existing mechanical equipment and installing walls, floors, electrical fixtures, heating and air conditioning in the expansion area and installing partitions, facades, new electrical fixtures and floor repairs in the existing service department area.

Although from a construction standpoint the project consisted of straight-forward standard components, the customer-imposed constraint of requiring daily operations to be maintained at a minimum of interruption during

construction increased the difficulty of construction scheduling. It should be noted that this constraint is not unusual in most public works environments. Since the project required utilization of a majority of the building trades and was estimated to cost approximately $80,000, using total in-house accomplishment, it fell into the class of being representative of a large number of typical renovation projects accomplished in the public works environment.

5.2 Decision Categories

The first step in applying DCPM to the project is the same as in CPM; namely, the network construction phase. However, the major difference between DCPM and CPM in this step is the identification and listing of feasible alternative methods of accomplishing an activity rather than stating only one method and eliminating from further consideration all of the remaining feasible alternatives.

To aid in the process of decision activity identification and alternative listing, activity decision choices were classified into five general categories. These categories were as follows:

(1) Contractual - Can the activity be accomplished by contract vice in-house? This type of decision would

be considered for: (a) the lack of a specific construction skill in-house necessary for accomplishing a particular work activity, or (b) to provide a technqiue for short-term resource leveling, e.g. contract for a specific labor or equipment category which is over-committed during the time scheduled.

(2) Construction Operation Technique - Are there several different construction techniques presently available to accomplish the activity? This type of decision would be considered for those activities which could be accomplished by: (a) total or partial pre-fabrication of components, (b) use of different size or type of equipment, or (c) use of different construction materials.

(3) Phasing - Can a group of activities be accomplished at an earlier or later date than presently being considered? This type of decision requires that the project network be decomposable into more than one subnetwork which is logically self-contained but dependent upon another subnetwork(s) but not necessarily in a predetermined order or time.

(4) Scheduling - Does the activity require being accomplished only during a specified time span, e.g. only during non-work hours?

(5) Resource Leveling - Can different amounts of a resource be applied to the activity to obtain different rate of accomplishment?

5.3 Network Development

Figures (4) through (9) present the DCPM project network. Due to the customer imposed constraints, the existing floor plan and the new floor plan, the work sequence decomposed readily into four parts, each consisting of a specific area of the building. This is represented by Subnets #1 through #4 (Figures (5) through (8)). The customer, due to operational considerations, required that Subnets #1 and #2 be accomplished in sequence whereas Subnets #3 and #4 could be accomplished either in sequence or simultaneously. Subnet #5 (Figure (9)) represents the simultaneous network of Subnets #3 and #4.

It should be noted at this point that actual project network developed by the PWC consisted of Subnets #1, #2, #3 and #4 (Figure (4)) with no alternatives and total in-house accomplishment.

Decision activities S21, S46, S71, S88 and S99 are examples of the construction operation technique class of decisions. Decision activity S65 is a phasing type decision, e.g. whether to do Subnets #3 and #4 sequentially

or simultaneously. Subnets #1 and #2 are also of the phasing type but are constrainted in sequencing. Decision activity S30 is a scheduling type decision since the work required could be performed only during the weekend.

Additionally, S30 was also of the resource leveling type in that for the work to be accomplished in one weekend required additional manpower and equipment. All of the remaining decision activities were of the contractual type.

It should be noted that although resource leveling on specific activities can be accomplished by applying resource alternatives to each activity, it is infeasible to resource level every activity in the project network due to the combinatorial problem. Additionally, since the inputs to the DCPM program are only time, costs, precedence and constraints, resource leveling over the entire project cannot be accomplished by the DCPM models.

After the network construction phase was completed, the time and costs for each activity and decision alternatives were estimated. The time for those activities which would be accomplished in-house were estimated using the Engineered Performance Standards developed for normal estimating by the PWC and a "normal" level of labor and equipment applied. Excess labor and equipment were

considered only for decision alternative S30,1 and cannot be thought of as a "crashing" level in the CPM sense. For those activities that would be performed by contract, the Engineered Performance Standards were used only as a general guide for estimating time. Most of these latter estimates cannot be considered precise but are used to illustrate the method of using DCPM. From the time estimates for each activity, costs were generated using local wage rates, which included a fixed rate overhead charge. The overhead charge added into the wage rate was based on historical operating performance. These wage rates were applied to all direct and indirect labor estimates. Material costs and historical equipment operating/maintenance rates were also applied to each activity. The costs for those activities that would be contracted included estimated construction overhead and profit. Although this procedure for allocating overhead costs to individual activities may not be the most precise or realistic method available, it does allow for direct comparison of the total project solution costs and the illustration of the model's application.

Although the PWC does not use reward payments and penalty costs for incentives to meet completion date requirements, these incentives could be thought of as

organizational opportunity costs. In its most simplified form, these organizational opportunity costs would be labor output per day. Based on historical data, the labor output per day was about $100.00. This value was used in developing the network solutions shown in Appendix A. However, it should be noted that the DCPM algorithm used for this project considered these organizational opportunity costs for determining the number of optimal solutions to be considered. Thus, if no opportunity costs were used, the number of optimal solutions would be increased, whereas if an extremely high value were used, the number of optimal solutions would be decreased.

5.4 Network Solution

Once the time and costs have been generated, the network must be reduced and solved for the optimal solution time. Since the project network was fairly straight-forward, the reduction was performed manually, requiring one man-day of effort. In those cases of more complex network, the reduction should be accomplished by computer using the algorithm developed by Crowston.[29]

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[29] Crowston, "Decision CPM: Network Reduction and Solution," op. cit.

The computer programs used to solve the reduced network were developed by Wagner,[30] and are described and listed in his thesis. The input required is the number of decision nodes, required completion date, reward payments, penalty costs, decision alternative numbers, decision alternative time and cost, network precedence list, and interdependency constraints. All of the input is taken directly from the reduced network.

After the network is reduced, the DCPM algorithm is used to determine the alternatives that produce the optimal solution, that is, minimize Z (Equation 5). However, for this network, an additional step was required due to nesting of decision nodes. Decisions S1 and S65 are examples of nested decision nodes and can easily be understood by observing the reduced project network, Figure (10). If, for example, alternative S65,1 is selected, then the path formed by S65,2 and the subsequent decision alternatives cannot be selected. Similarly, if S11 were selected, then the paths formed by S12 and S13 cannot be selected.

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[30] M. H. Wagner, Solution of Decision CPM Networks (Unpublished Massachusetts Institute of Technology Master's Thesis, June 1968).

Although the general formulation of DCPM presented in Chapter 3 allows for the nesting of decision nodes, the computer program that was used for this thesis would have required excessive interdependency constraint expressions, resulting in substantial increases in computer time. Thus, the reduced network required further decomposition in order to be solved. The total project reduced network, Figure (10), was decomposed into four subnetworks, as follows:

Subnetwork #1:	consisted of Subnets #1, #2, #3 and #4
Subnetwork #2:	consisted of Subnets #1, #2 and #5
Subnetwork #3:	consisted of Decision S-3 alternatives
Subnetwork #4:	consisted of Decision S-13 alternatives

Subnetworks #1 and #2 optimal solution times, costs, and decision alternatives were computed with the results shown in Appendix A. The output is in the form "Bounds", time in days, incremental cost, and "Path" with the selected decision alternatives. This output form denotes the optimal solution for the critical path length of x days with the corresponding total cost being the

incremental cost plus the "T COST" value. Subnetworks #3 and #4 optimal solution time, costs and decision alternatives were computed by inspection from the reduced project network, Figure (10). The resulting optimal solution times and costs for each subnetwork are plotted in Figure (12).

Figure (12) presents a wide range of alternatives for project execution assuming no defined completion date. The project manager can choose any one of the network solutions as an execution plan. He can readily see the amount of time and cost advantage one plan has over another. However, if a completion date for the project were specified, say for example, 165 days, then the project manager would choose an execution plan from:

a.	Subnetwork #1	163 days @ a cost of $63,370
		161 days @ a cost of $63,550
		155 days @ a cost of $63,590
b.	Subnetwork #2	159 days @ a cost of $54,965
		151 days @ a cost of $55,185
		146 days @ a cost of $55,395
		136 days @ a cost of $55,615
c.	Subnetwork #4	150 days @ a cost of $93,150

Additionally, a rapid determination can be made of the impact of customer imposed constraints in terms of time and costs. For example, if the customer stated that due to operating conditions it would be more desirable to proceed with construction in a sequential manner using Subnets #3 and #4 instead of Subnet #5, then the resulting optimal execution plan would require an increase of 17 days and $8,675.00 over the optimal plan utilizing Subnet #5.

If the reduced network had not been decomposed into the four subnetworks, then the network time cost curves plotted in Figure (12) would be reduced to one discontinuous curve consisting of only those points for which the time and cost were optimal.

The network DCPM computation was performed on the MIT Compatible Time Sharing System using an IBM 7090 computer. Subnetwork #1, which contained 18 decision nodes, required 78 seconds for the ten optimal time/cost solutions while Subnetwork #2, which contained 15 decision nodes, required 26 seconds for the five optimal solutions. This relatively small amount of computation time (and cost) suggests that for the additional effort spent in explicitly identifying

activity alternatives and generating the corresponding time and cost estimates, a wide range of execution plans are developed from which the most desirable plan can be selected.

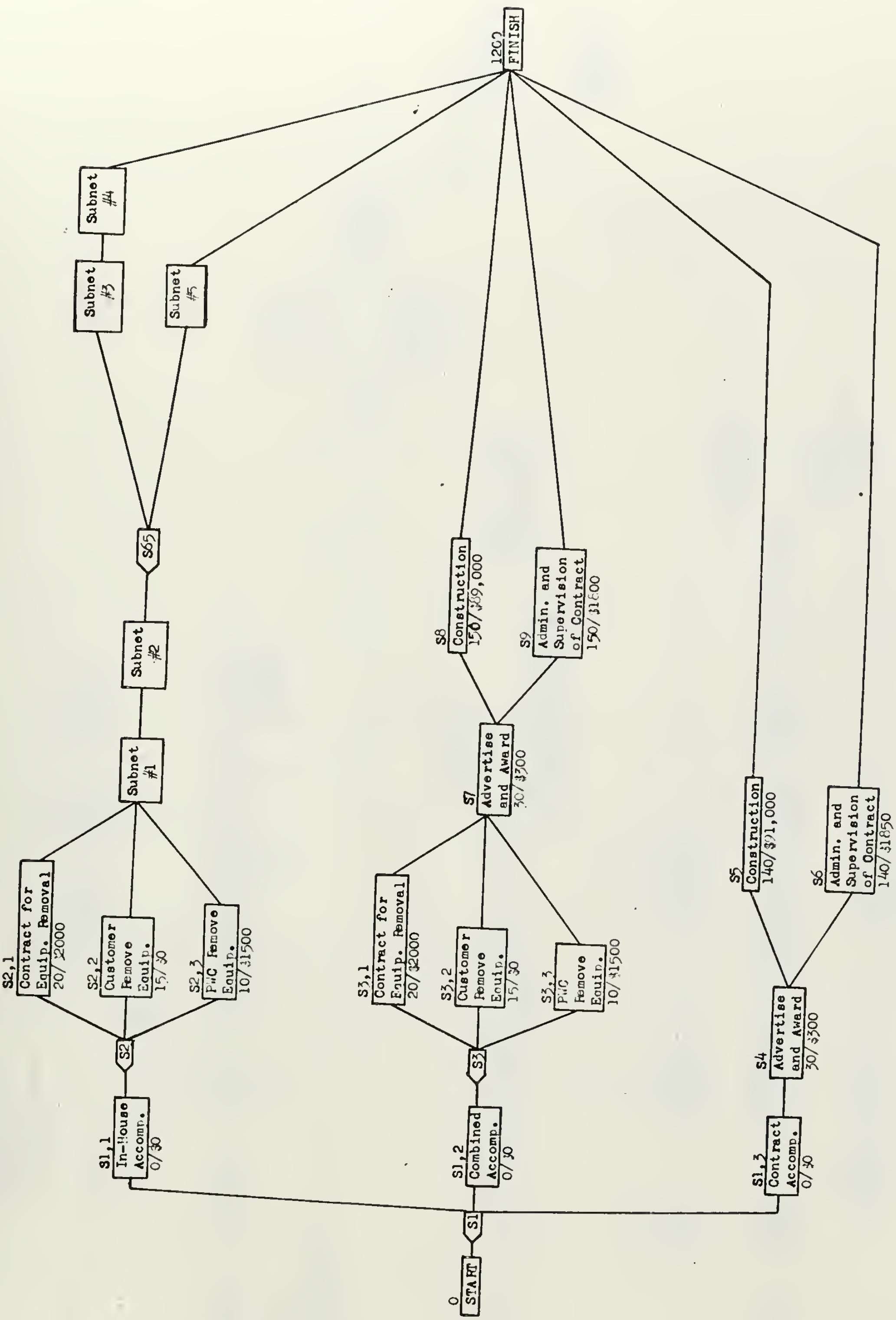

FIGURE 4 BASIC PROJECT NETWORK

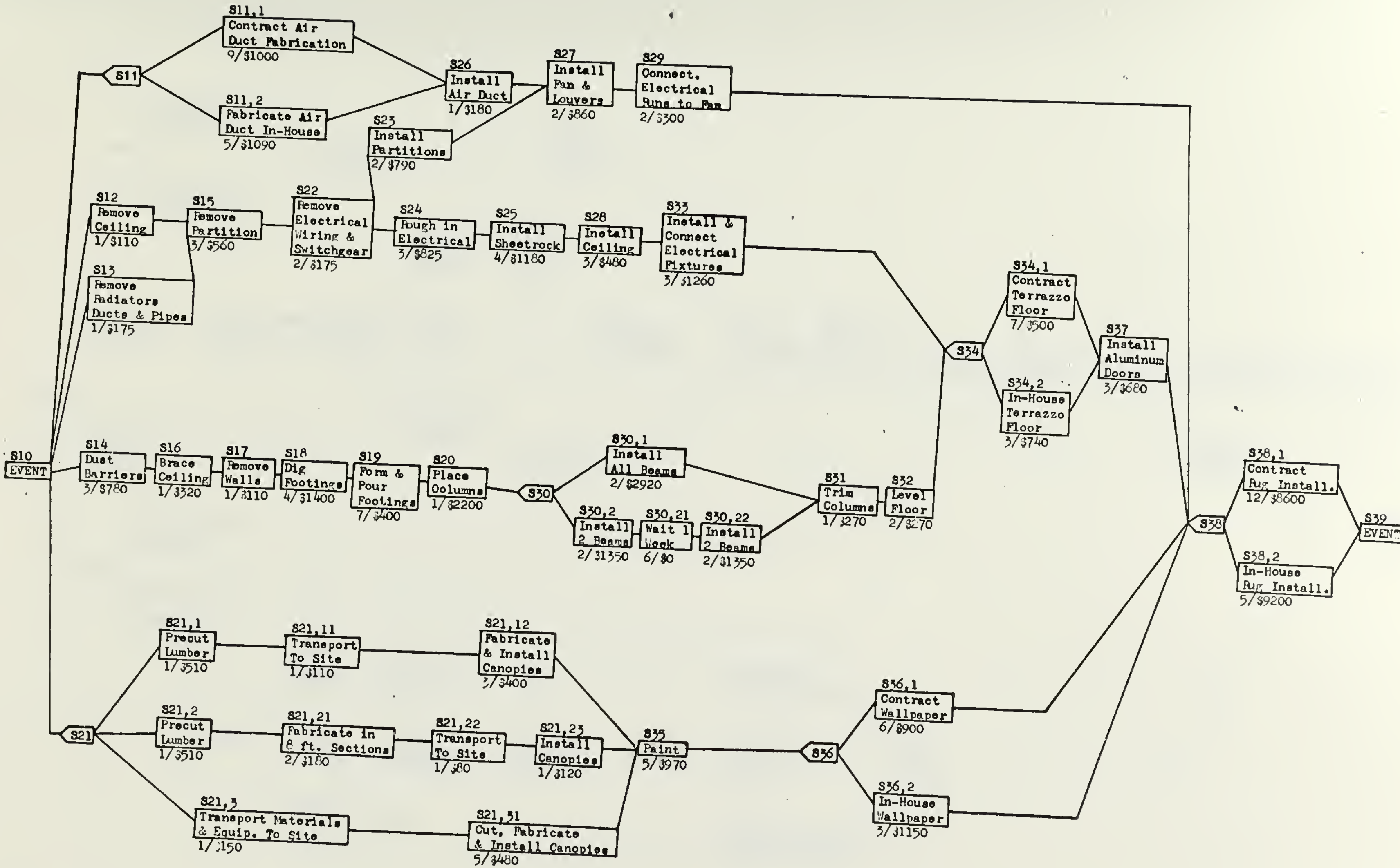

FIGURE 5 SUBNET #1

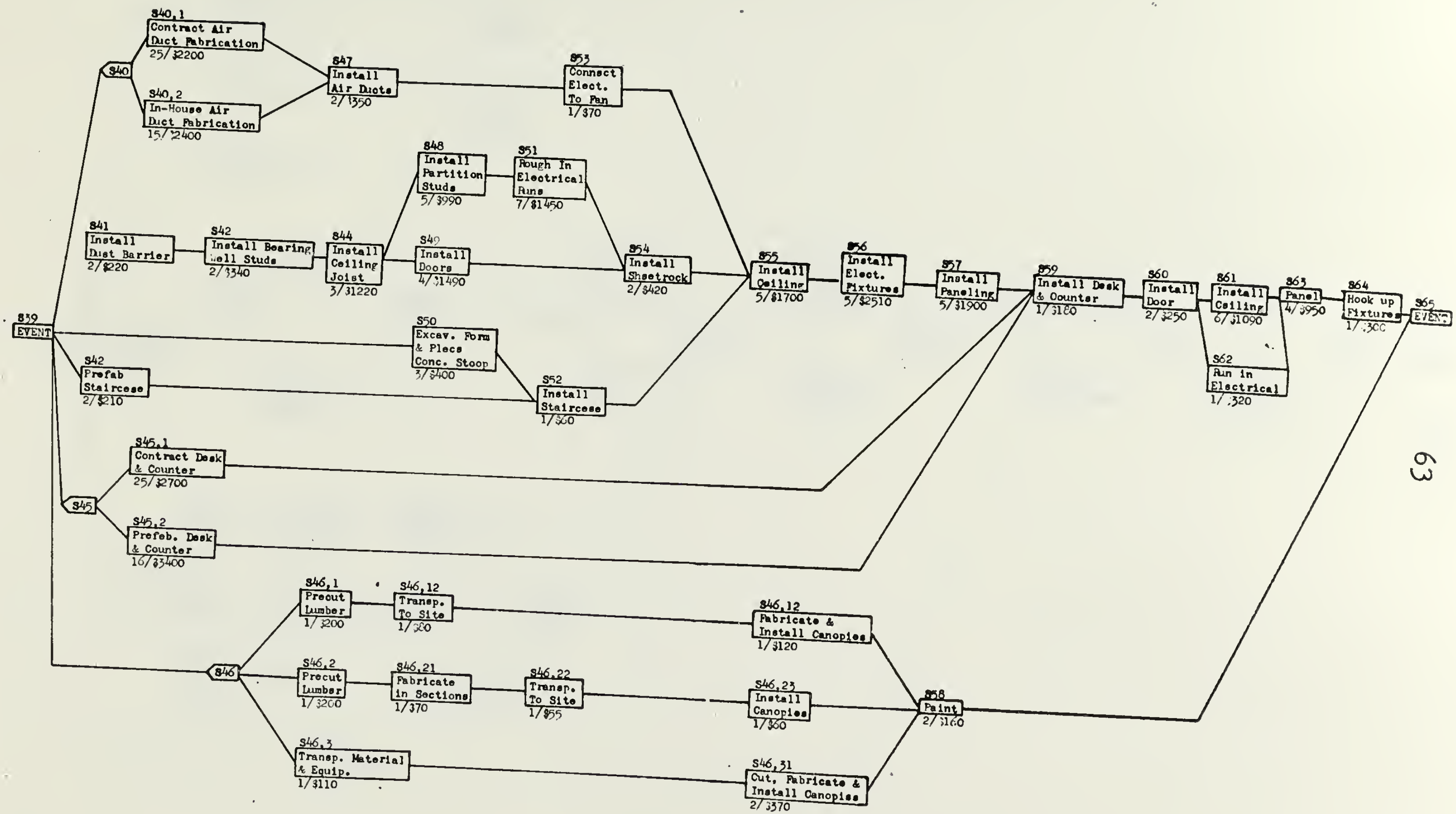

FIGURE 6 SUBNET #2

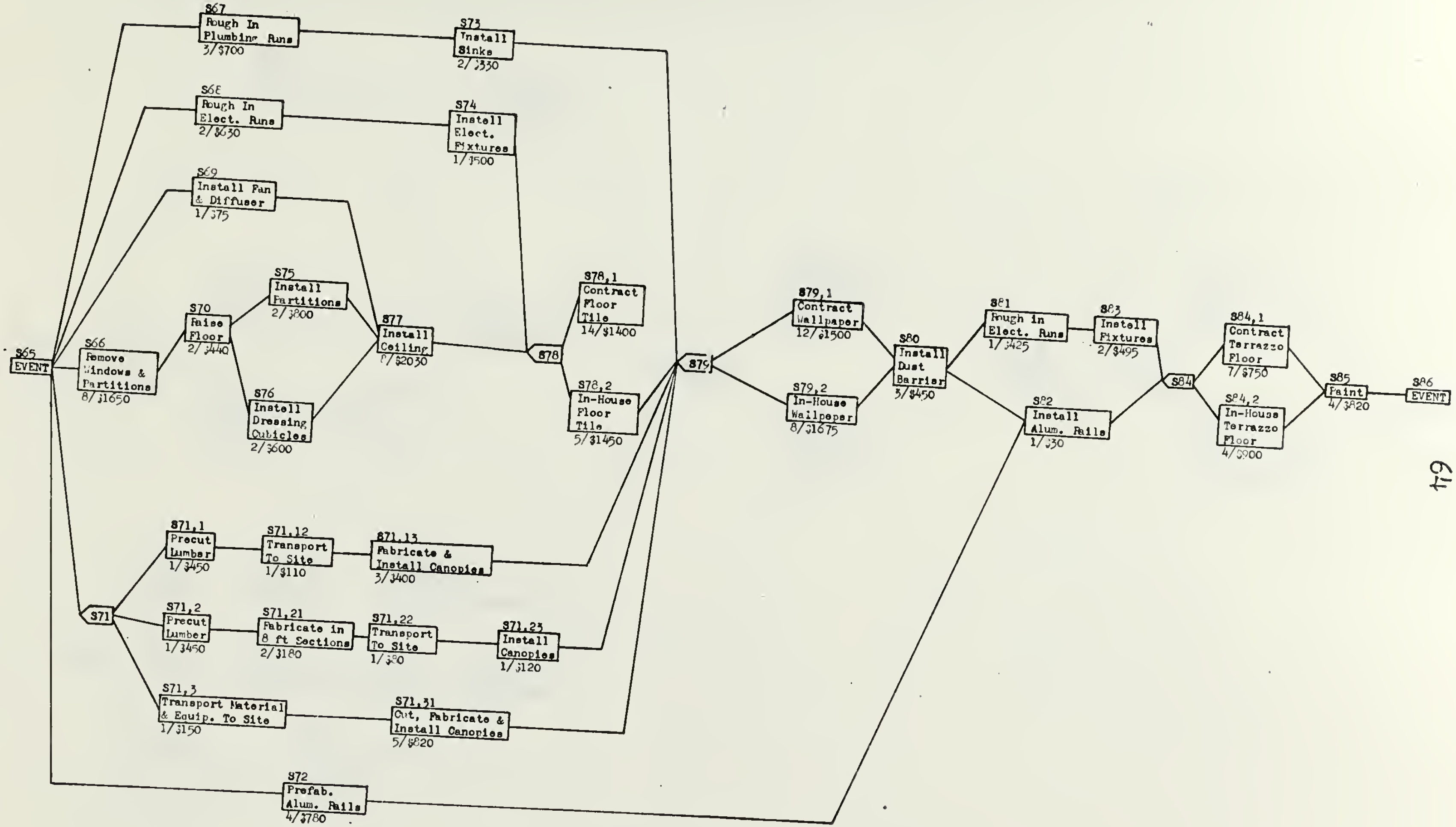

FIGURE 7 SUBNET #3

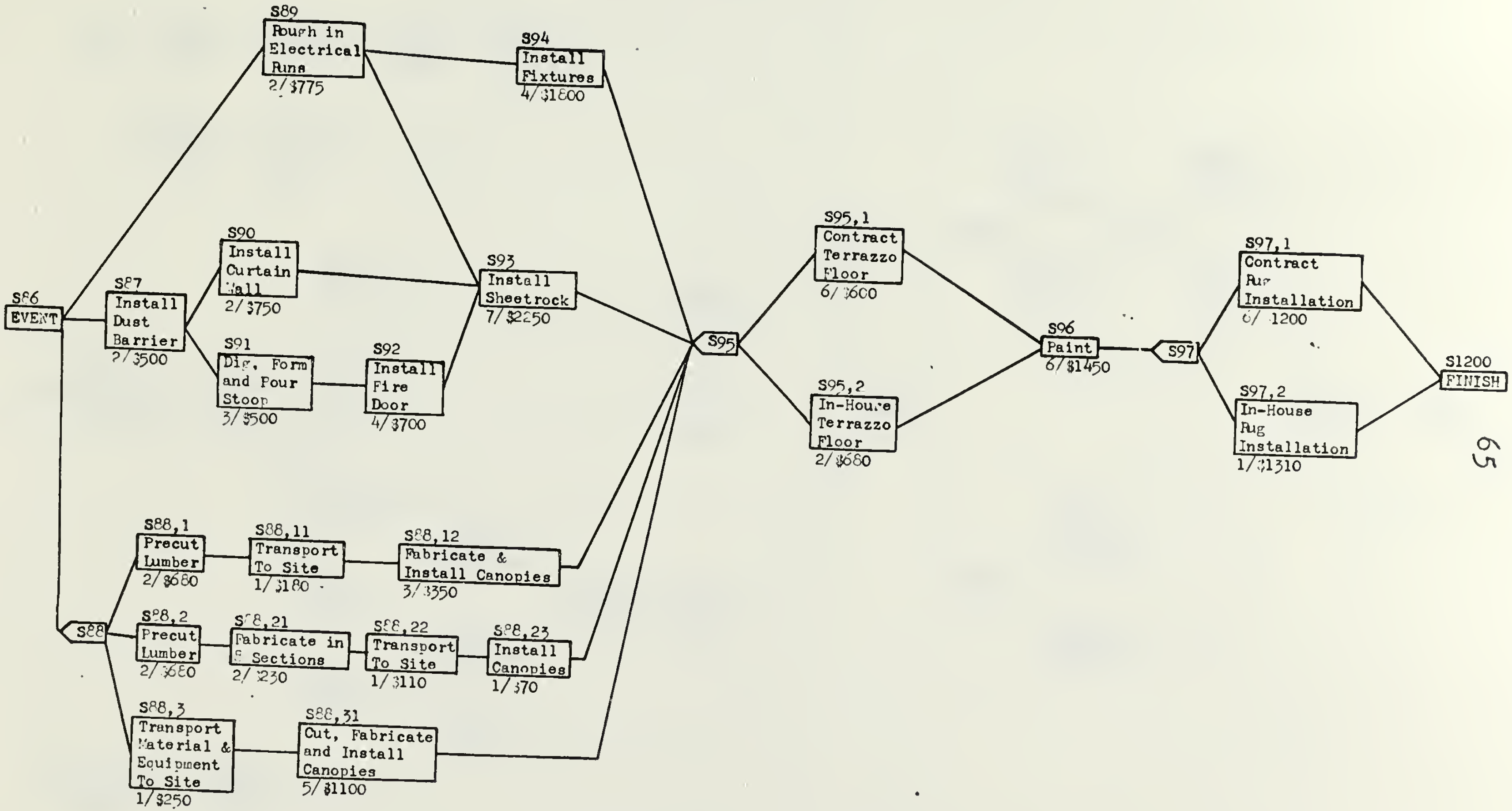

FIGURE 8 SUBNET #4

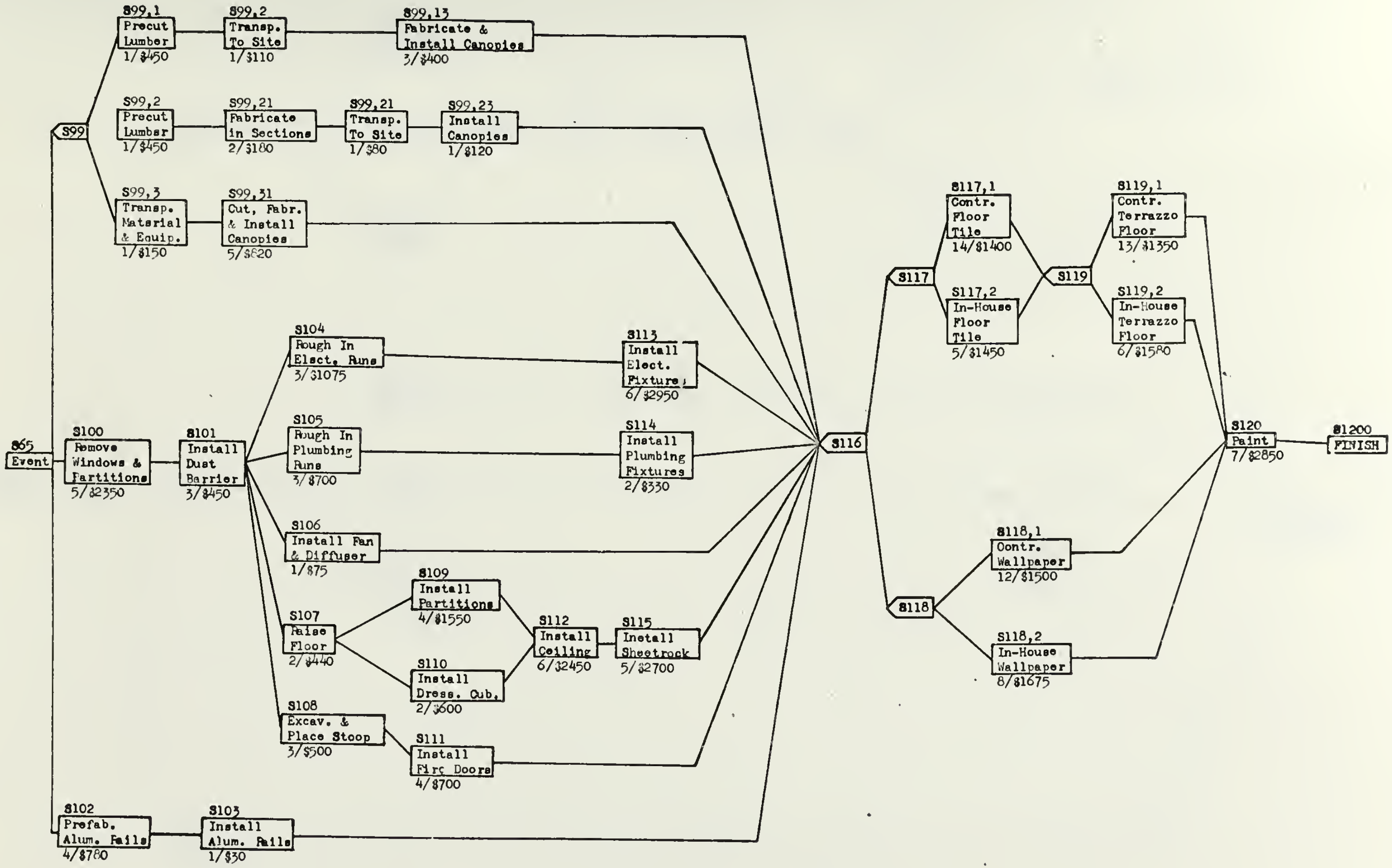

FIGURE 9 SUBNET #5

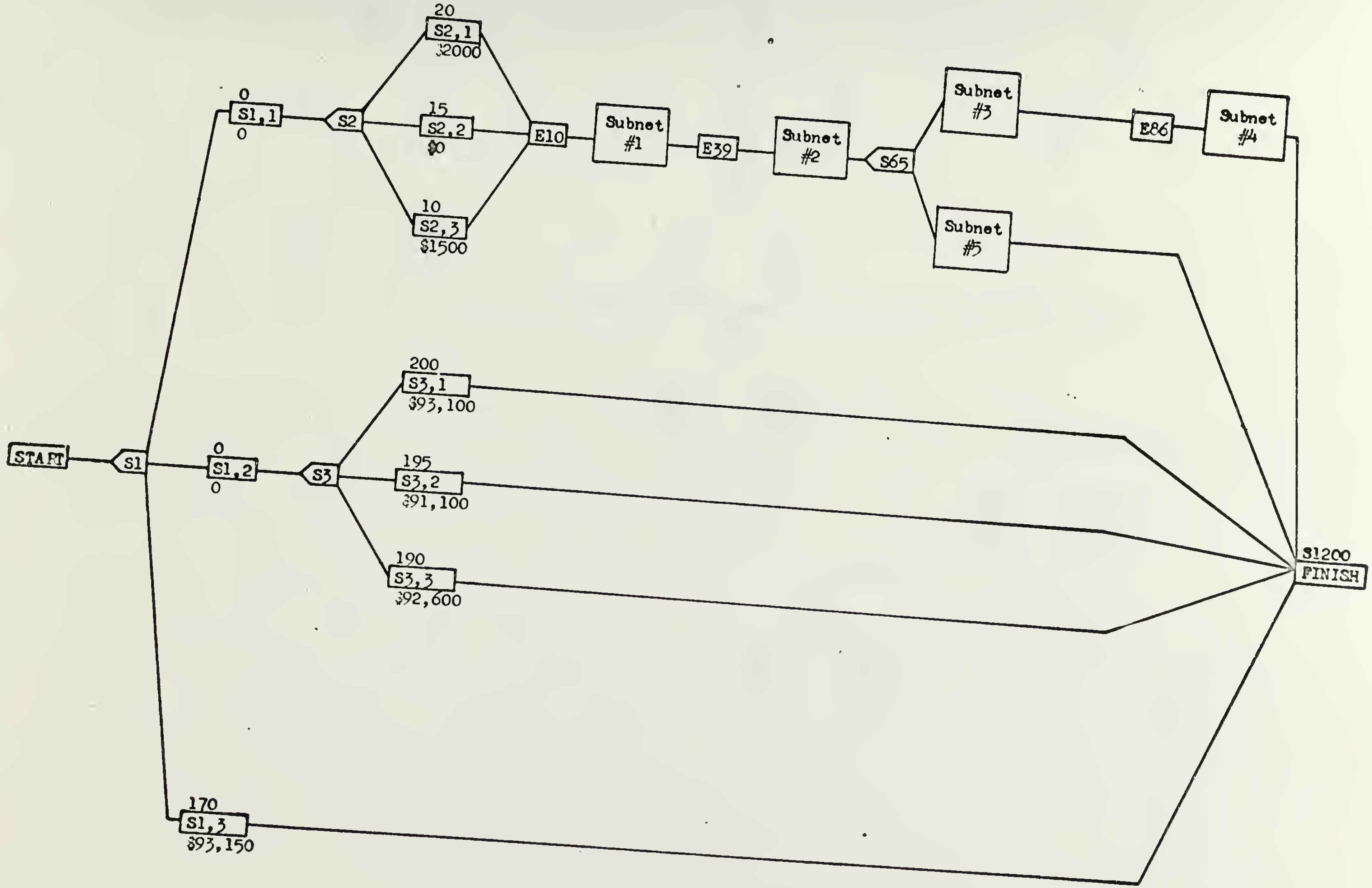

FIGURE 10 REDUCED PROJECT NETWORK

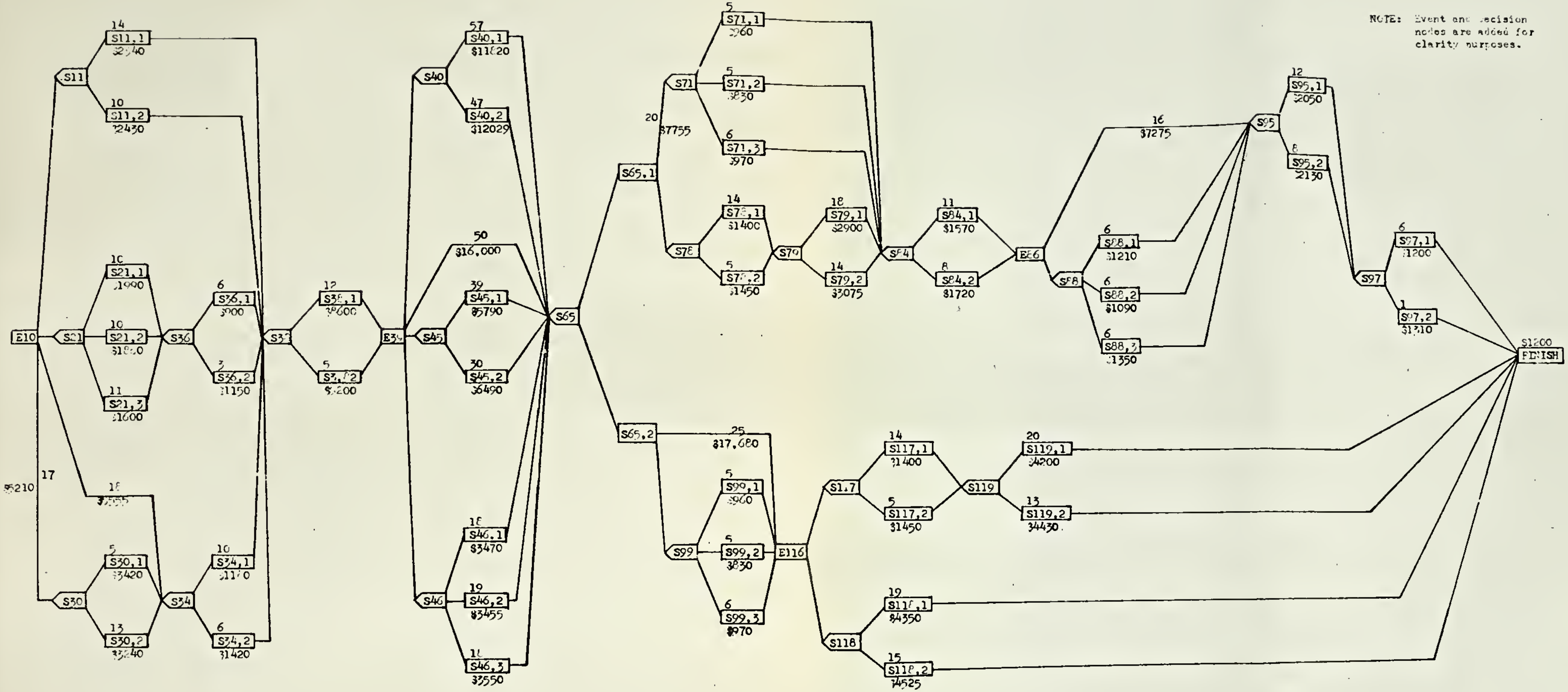

FIGURE 11 REDUCED SUBNETS #1, #2, #3, #4 AND #5

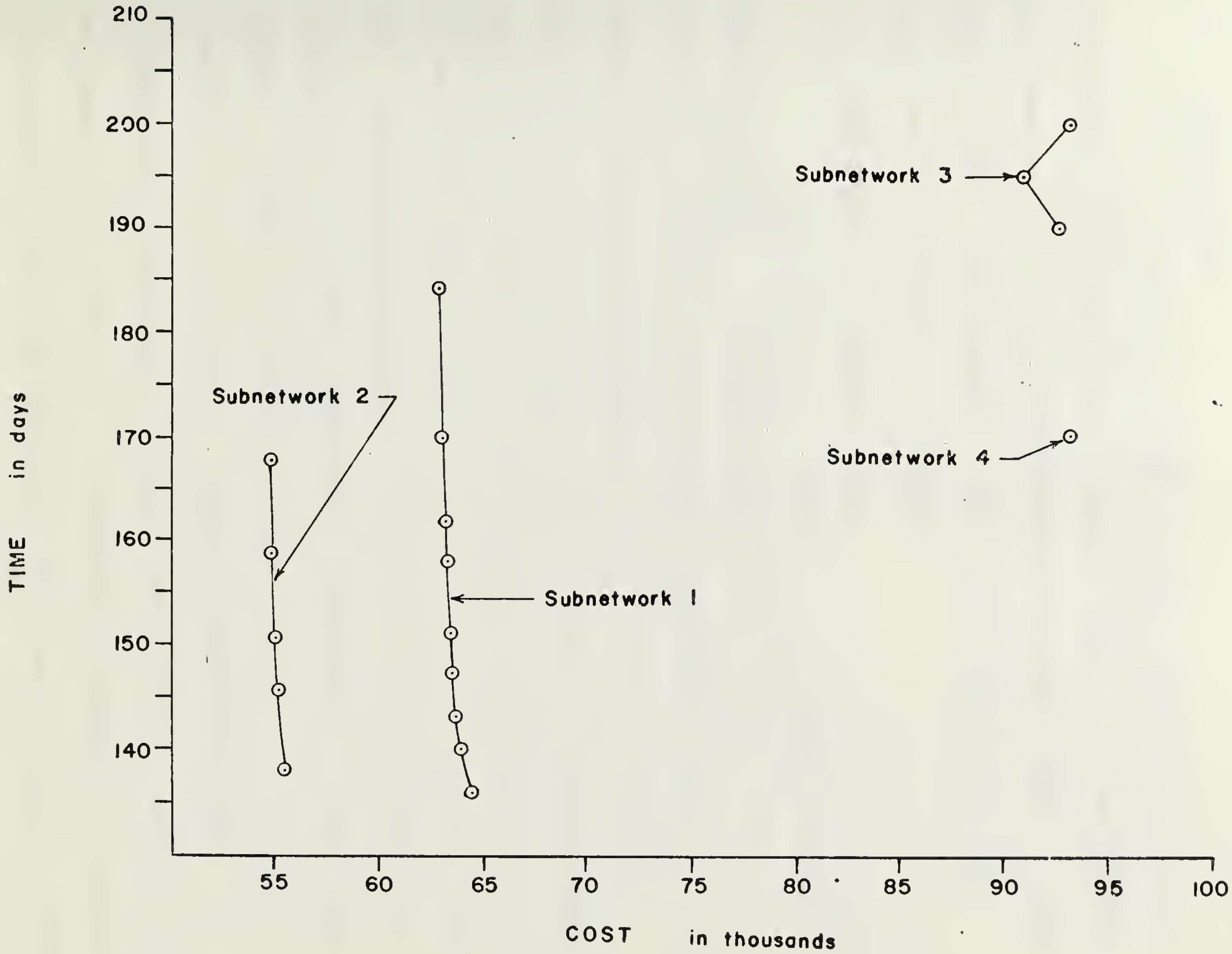

FIGURE 12 NETWORK TIME - COST CURVES

CHAPTER 6
SUMMARY

6.1 Conclusions

The application of DCPM to the renovation project discussed in the previous chapter leads to several conclusions about the applicability of using DCPM in the Public Works environment. The conclusions are both positive and negative in nature.

The positive aspects are:

1. Consideration is given to all feasible alternative methods of accomplishing an activity. This condition creates two extremely important benefits. First, during the construction planning process, explicit definition of each alternative method of accomplishing an activity is required. This explicit definition is translated to the DCPM model only in terms of time and cost, but the project personnel involved in the planning are required to totally understand the method. This first benefit leads to the second benefit which is difficult to quantify but is known as improved communications. No longer are the project manager and project superintendent allowed to be thinking of different methods of accomplishing an activity with the same time and costs because the method will have been explicitly defined and, of course, will be

feasible. These two benefits in themselves are reason enough to apply the model even if cost savings are not attainable.

2. Decision making is accomplished sequentially over the project time span. The execution plan selected from Figure (12) initially sets the selected activity alternatives. As the project progresses, the network is updated, optimal solution time/costs are generated and a new optimal execution plan selected which may or may not change the initially selected decision alternatives.

The negative aspects are:

1. In comparing the solution in Appendix A and the execution process shown in Figure (2), it is readily apparent that DCPM cannot provide the detailed information regarding the scheduling of labor, material and equipment. The model only considers the parameters of time and costs which fall short of providing the total information necessary for the total planning and execution process. One only has to compare Appendix A with the range of scheduling output options available in ICES Project I to see the degree of detailed information needed to effectively and efficiently manage a construction project.

2. As a corollary to #1 above, resource balancing over more than several specific activities becomes

infeasible. For example, to resource balance the described project, the number of decision nodes would have increased from twenty-four to one-hundred and nine with each decision alternative representing a discrete level of manpower and an equipment utilization. This significantly increases computation time with no facility for constrainting the maximum level of a resource. Therefore, resource balancing can only be accomplished by using another model such as SPAR or RAMPS after the optimal execution plan has been selected.

3. The model suffers from the problem that is associated with the CPM model, namely, the times and costs generated for each activity and activity decision alternatives are deterministic.

4. By reviewing Figures (4) through (9), it is readily apparent that the graphic representation of the network is totally impractical for a working control tool.

5. Since costs and time are estimated for each activity, to be totally effective as a control tool, the collection of project progress data must be in the same level of detail; namely, by activity. In the PWC case, this is impossible because cost collection is done by total

project instead of individual project activity. For the model to be used as a control tool, both time and cost collection must be on an activity basis.

6. Although the reduced network developed in this thesis was readily decomposable to by-pass the decision node nesting problem, this may not always be the case. Thus, the computer programs used should be modified to readily handle the nesting of decision nodes.

Based on the above conclusions, it appears that the DCPM model is readily applicable on those projects that are large enough for normal CPM application. Its application will provide a more complete and comprehensive evaluation of the construction procedures during the planning phase. But, the model limitations in scheduling information, resource balancing and increased effort required in time/cost estimation must be recognized and understood.

6.2 Recommendations

Since the DCPM can provide a mechanism for more comprehensive construction planning in the Public Works environment, the following areas must be investigated or implemented:

1. Of utmost importance before implementing the DCPM model in an organization, an effective and detailed educational effort must be conducted on those affected personnel in order that proper application will be effected.

2. Future development effort must be directed toward adding the DCPM algorithm or program to an existing operating CPM model such as ICES Project I. This would allow for the continuous planning and execution with one common data base from which the desired information could be processed and obtained.

3. Immediate development effort should be directed toward improving the input-output section of the existing programs allowing nesting of decision nodes, and tying the network reduction program to the DCPM program.

4. Future application effort should be directed toward the construction industry to study the feasibility of the model's use on projects which are accomplished by a prime contractor's work force and several sub-contractors' work forces.

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APPENDIX A

DCPM NETWORK SOLUTIONS

The DCPM Network for the renovation project is shown in Figures (4) through (9). Operating on this network -- which consisted not only of decision alternatives, but also of normal activity nodes -- using Crowston's algorithm for network reductions produced the reduced DCPM network shown in Figures (10) and (11). Solution of the reduced network was accomplished using the computer programs MASTER3, TEST3, CPM3, BEST3, and TIME3 listed in Wagner's thesis.

The required input was taken directly from the reduced network, Figures (10) and (11), and consisted of:

a. number of decision nodes
b. project completion time
c. finish node number
d. reward payments
e. penalty costs
f. number of interdependency constraints
g. decision alternative
h. decision alternative time
i. decision alternative cost
j. precedence relationship (list)
k. interdependency relationships

The output stating the solutions is in the following form:

BOUNDS xxxx (time) xxxx (incremental cost)

PATH xxxx xxxx xxxx . . . (decision alternative number)

TCOST = xxxx (basic cost)

R xxxx + xxxx (system operating time)

The total cost for each solution is TCOST + incremental cost. Additional output was provided which was of interest to the programmer for determining the relative efficiency of the programs. This information has been deleted since it served no useful purpose in this thesis.

```
SUB-NETWORK #1

  DCPM STARTED
EXECUTION.
234
 BOUNDS      184.0       0.
     PATH     22     111    213    302    341    361    381    401    451    462    651
             712     781    791    842    882    951    972
 BOUNDS      170.0     160.0
     PATH     22     111    213    302    341    361    381    401    451    462    651
             712     782    791    842    882    952    972
 BOUNDS      162.0     340.0
     PATH     22     111    213    301    341    361    381    401    451    462    651
             712     782    791    842    882    952    972
 BOUNDS      158.0     420.0
     PATH     22     111    213    301    341    361    381    401    451    462    651
             712     782    791    841    882    952    972
 BOUNDS      151.0     620.0
     PATH     22     111    213    301    341    361    381    402    451    462    651
             712     782    791    841    882    952    972
 BOUNDS      147.0     795.0
     PATH     22     111    213    301    341    361    381    402    451    462    651
             712     782    792    841    882    952    972
 BOUNDS      143.0    1035.0
     PATH     22     111    213    301    342    361    381    402    451    462    651
             712     782    792    841    882    952    972
 BOUNDS      140.0    1235.0
     PATH     22     111    213    301    342    361    381    402    451    462    651
             712     782    792    842    882    951    972
 BOUNDS      136.0    1635.0
     PATH     22     111    213    301    342    361    382    402    451    462    651
             712     782    792    841    882    952    972
TCOST=   62930.00


R 73.483+4.783
```

```
SUB-NETWORK #2

  DCPM STARTED
EXECUTION.
652
 BOUNDS      168.0     0.
     PATH     22     111   213   302   341   361   381   401   451   462   652
              992    1171  1181  1191
 BOUNDS      159.0    50.0
     PATH     22     111   213   302   341   361   381   401   451   462   652
              992    1172  1181  1191
 BOUNDS      151.0   270.0
     PATH     22     111   213   301   341   361   381   401   451   462   652
              992    1172  1181  1191
 BOUNDS      146.0   480.0
     PATH     22     111   213   302   341   361   381   402   451   462   652
              992    1172  1181  1192
 BOUNDS      138.0   700.0
     PATH     22     111   213   301   341   361   381   402   451   462   652
              992    1172  1181  1192
TCOST=  54915.00


R 22.050+3.900
```

APPENDIX B

LIST OF FIGURES

Thesis
H2929
122578
Harris
The applicability of
Decision Critical Path
Method to the Public
Works environment.